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STUDY OF FATIGUE FAILURE OF COMPOSITE MATERIALS

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STUDY OF FATIGUE FAILURE OF COMPOSITE MATERIALS

by

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The use of composite materials in U.S. Navy aircraft and other vessels has become increasingly popular due to the composites' high strength to weight ratio. The nature of these military structures causes them to be exposed to high amounts of vibrations and cyclic loads, which lead to fatigue and eventual failure. The main objective of this research is to develop a reliable model to predict fatigue failure of composite materials in order to determine the service life of these military structures. This study determined the correlation between the fatigue failure of the glass fiber and the fatigue failure of the fiber and epoxy matrix composite. Glass fiber and composites with differing orientations were tested at various strain rates from 0.03–0.07 and were compared. A mathematical expression was created to model the exponential decrease of the elastic modulus with the number of cycles and to predict the failure cycle. The mathematical model is able to predict the failure cycles within 12% of the experimental results and follows the same trend of decreasing elastic modulus for both the fiber and the composite, showing a correlation exists between the failure behavior of fibers and the failure behavior of composites.

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STUDY OF FATIGUE FAILURE OF COMPOSITE MATERIALS

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ABSTRACT

The use of composite materials in U.S. Navy aircraft and other vessels has become increasingly popular due to the composites' high strength to weight ratio. The nature of these military structures causes them to be exposed to high amounts of vibrations and cyclic loads, which lead to fatigue and eventual failure. The main objective of this research is to develop a reliable model to predict fatigue failure of composite materials in order to determine the service life of these military structures. This study determined the correlation between the fatigue failure of the glass fiber and the fatigue failure of the fiber and epoxy matrix composite. Glass fiber and composites with differing orientations were tested at various strain rates from 0.03–0.07 and were compared. A mathematical expression was created to model the exponential decrease of the elastic modulus with the number of cycles and to predict the failure cycle. The mathematical model is able to predict the failure cycles within 12% of the experimental results and follows the same trend of decreasing elastic modulus for both the fiber and the composite, showing a correlation exists between the failure behavior of fibers and the failure behavior of composites.

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I. INTRODUCTION

The use of composite materials, especially fiber-matrix composites, has become increasingly popular due to their high strength to weight ratio and their ability to be custom made for use. Fiber-matrix composites are widely used in aerospace engineering including the use in military aircraft. The U.S. Navy uses composite materials in many of their aircraft, has incorporated them into warships, and is designing a composite propeller for the next-generation submarines.

The composite materials that make up the shell of a jet or the propeller of a submarine will be subject to large loads and vibrations that will ultimately lead to fatiguing and fatigue failure. It is necessary to understand and be able to predict fatigue failure of composites in order to determine the service life of an aircraft, or other structure, before catastrophic failure.

The focus of this thesis will be on fiber-matrix composites made out of glass fiber and epoxy resin. The over-arching goal of this research is to create multiscale model that will be used to predict the fatigue failure of composites. The focus of this study will mainly be on determining the correlation between fatigue failure of the resin and fiber with the fatigue failure of the composite. This will pave the way for further studies in creating a multiscale model. Proving the validity of this fatigue failure model will allow it to be easily used in the prediction of the service life of military aircraft and other structures to ensure the safety of military service members and their equipment.

A. INTRODUCTION TO COMPOSITE MATERIALS

A composite material is characterized by a combination of two or more materials that differ in physical properties [1]. As mentioned earlier, the focus of this study will be on fiber-matrix composites. For this type of composite, the matrix acts as a protectant for the fibers, holding them in place, while the fibers themselves are used to increase the strength and stiffness, reinforcing the structure as a whole [1]. Figure 1 shows the layout of a typical composite.

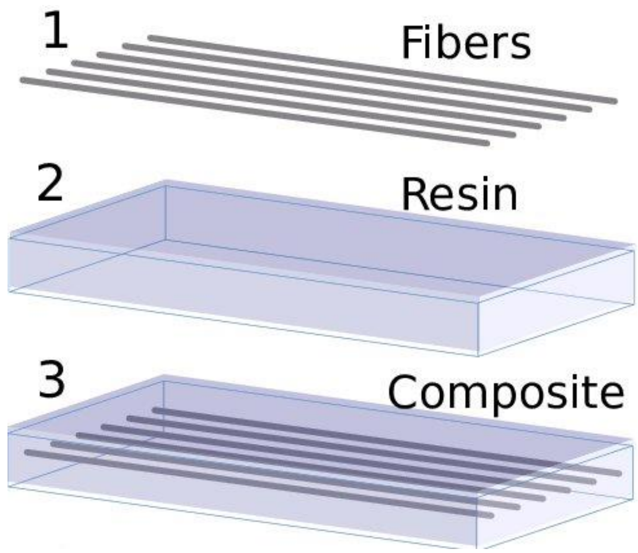

Figure 1. Simple Fiber-Matrix Composite. Source: [2].

The fibers used in composites are aligned in a single direction to allow for extremely high tensile strength and high strains in a certain direction. This anisotropic property of fiber-matrix composites makes them incredibly complex structures but also gives several advantages over typical metal alloys used in engineering. Fiber-reinforced composites have been replacing metals for years because of their superior strength to weight ratio; composites are much lighter than metals without sacrificing strength. The unidirectional layout of composite structures also allows them to be custom designed for use and applications, meaning that if strength needed to be increased in one direction, a composite could easily accomplish this without having to increase material use (and weight) like you would using a typical isotropic metal alloy. They also provide many other advantages such as being corrosion-resistant and insulators.

B. COMPOSITES IN THE NAVY

As stated earlier, composites are becoming increasingly popular and are being used to replace metal alloys in engineering. Some applications include the use in sports, biomedical applications, trusses, shells for automobiles, aircraft or other vessels, etc. The U.S. Navy is also increasing its use of composites in military craft in equipment. Many naval airplanes and warships are starting to use more and more fiber matrix composites and it is expected that future aircraft and vessels will be composed of about 90% weight of composite material [3]. The first use of composites in the military began in the 1940s in warships in order to decrease the weight and corrosion of the vessels [4]. It was discovered that the composites were still able to maintain the reliability of the craft and they began to incorporate more and more composites into the Navy. Today, composites are used in vessels frames, doors, aircraft tails, floors, blades, rotors, pins, tailscrews, fuselages, etc. [5].

However, the increasing use of composites does not mean increased safety. The Federal Aviation Administration (FAA) monitors the use of composites on aircraft and has specific regulations for approved uses. Each part that uses composite materials must undergo fatigue testing and there must be fatigue limits developed for each component, including service life, cycles until failure, environmental factors, etc. [6]. These regulations are so critical because of the nature of aircraft; materials that make up aircraft are exposed to high levels of vibrations and cyclic stresses which causes fatigue. Fatigue is found to be the most common cause of aircraft failure and is therefore a critical failure mode to understand when designing anything [7].

C. INTRODUCTION TO FATIGUE

Fatigue occurs when exposed to repeated stresses that are typically below the yield stress. The cyclic stress causes micro-cracks which propagate and grow with increasing cycles, eventually leading to failure. Because of this, it is important to be able to predict the service life of a material and know how many cycles it can undergo until failure. An S-N curve shows the relationship between cyclic stress amplitude and the number of cycles until failure. A typical S-N curve is shown in Figure 2.

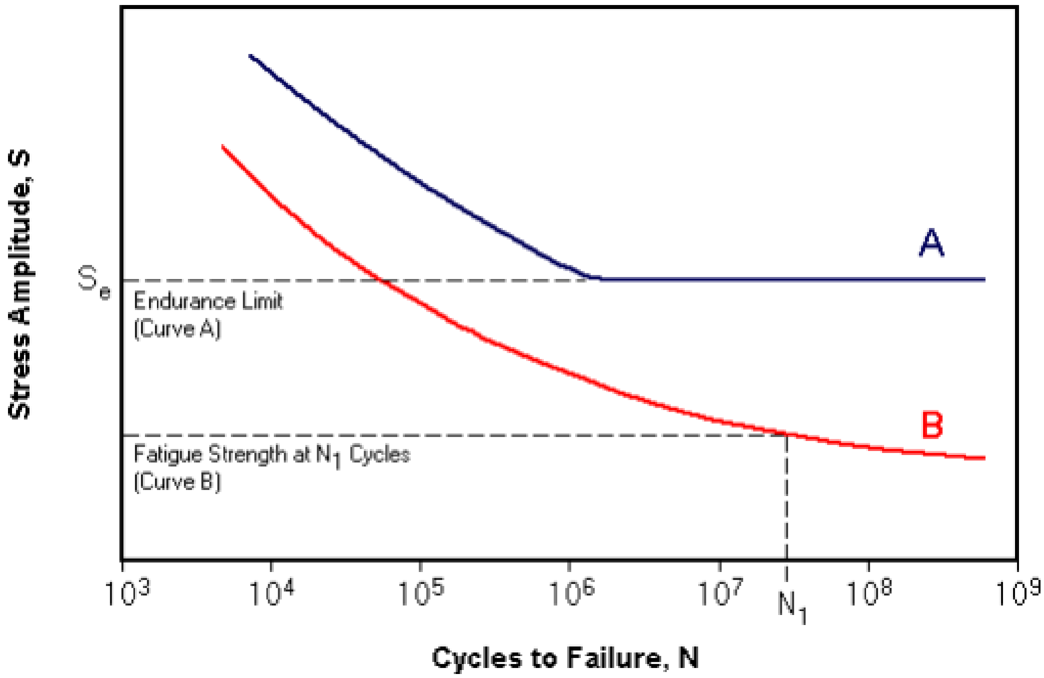

Figure 2. Typical S-N Curve. Source: [8].

These curves are extremely helpful in determining the service life of a material because they show the number of cycles until failure at any given stress. For some materials, the curves can even show the endurance limit, or infinite life of a material. In the figure, for material A, the point at which the curve has flattened out shows the point at which with any stress at or below Se, the material will have infinite life and not fail due to fatigue. These curves are created through fatigue testing of materials at different stress amplitudes, counting the cycles until failure and are used in the design of structures to help determine the service life.

For typical metals, the damage and failure are fairly well understood; the fatigue cracks and propagation are much easier to predict than for composite materials because of the isotropic nature of metals [9]. For composite materials, they fail differently in tension than in compression and can incur degradation that is very difficult to detect. In order to comply with the FAA regulations, the performance of composite materials in this environment must be better understood.

The use of composites, although becoming more popular, is more expensive and more difficult to understand and predict than typical metals. However the advantages of composite materials prove to be essential for the needs of the Navy. For example, the lower weight of composites will allow for longer missions before refueling, and the use of composites will also lower the detectability of jets and warships [3]. The complexity of composites makes it very difficult to completely ensure the safety of military vessels and the members onboard. The purpose of this study is to find a relationship between the fatigue of fibers, matrix, and composites in order to create a reliable model that will predict the failure of composites and determine the service life of military craft before catastrophic failure. Few composite fatigue failure models currently exist and are constantly being improved. These models are explained below.

D. EXISTING MODELS FOR PREDICTING FATIGUE LIFE OF COMPOSITE STRUCTURES

As stated above, the anisotropic behavior of composite materials makes them complex and difficult to predict. Composite materials can fail in several ways including fiber breakage, fiber pullout, delamination, matrix failure, fiber-matrix debonding, etc. [10]. In addition to this, the failure of composite happens suddenly without warning [11]. Because of this, it is very important to understand and be able to predict this failure. Previous research explored composite damage on both the micromechanics scale and the macromechanics scale. A micromechanics approach entails modeling the microcracks within individual fibers. However, this approach is considered impractical and not desirable due to the large variations in these microcracks within a damaged composite material [10]. The other approach, a macromechanic scale approach, deals with larger-scale damage of the material vice microcracks and is much more practical. Research in this area has made significant strides in failure modeling; however, it still needs to be explored and understood further [10]. Previous models that exist are explained below.

One of the earliest fatigue models was that of Hahn and Kim [12], which proposes "that if property changes under fatigue loadings can be related to some structural damage, then material properties can be predicted." In this study, static tension, static fatigue, and proof testing were conducted on glass/epoxy composite materials. Static strength and fatigue life were tested for several specimens. The relationship was then checked by proof testing to see if the specimen would outlive the minimum expected fatigue life. Their test showed that a unique relationship does exist between the static strength and life through proof testing and assumed that a "specimen of a certain rank in the fatigue life distribution is assumed to be equivalent in strength to the specimen of the same rank in the static strength distribution" [12]. A few years later, Chou and Croman named this assumption the Strength-Life Equal Rank Assumption (SLERA) and summarized that the findings of Hahn and Kim show the "time rate of decrease of residual strength is inversely proportional to the residual strength to a certain power" [13]. This assumption is still widely used and followed in the analysis of the fatigue of composite materials and is used in other studies that have created fatigue models as well.

Other models predict the behavior of composites using Basquin's relation of S-N curves [14]. Other studies, such as those of Yang and Lui [13], and Chou and Croman [15] have created residual strength degradation models to predict the fatigue of composites. Chou and Croman also created a sudden-death model which assumes that the strength of the composite does not decrease after each cycle, but instead increases drastically during the final few cycles [16]. This is unlike the residual strength degradation models which assume that the "residual strength decreases monotonically" [15]. Both models are accurate in predicting the fatigue life of composites. Similarly to these models, a modulus degradation model by Wang and Chim [17] and a shear modulus degradation model by Wang and Goetz [18] were created to derive a theoretical fatigue life equation and a theoretical shear fatigue life equation respectively. Following these works, Hwang and Han [14] present a "more practical and applicable" theoretical fatigue modulus under the assumption that "the fatigue modulus degradation at an arbitrary fatigue cycle is followed by a power function of fatigue cycle." His model also proves to accurately predict fatigue life of glass fiber/epoxy composites.

Another interesting model is that of Christos Kassapoglou which predicts the fatigue life without any experimentally determined parameters or fatigue tests [19]. His methodology relies on the assumption that the "probability of failure during a single cycle is constant and independent of the current state or number of cycles up to that point" [19].

For his first model, he relates the probability (P) that a structure has failed to the number of cycles until failure (N) and the probability of failure for any given cycle (p) using the following equation from [19]

$$P = Np(1-p)^{N-1}\,.$$

He then goes into detail describing how to determine ‘p’ and how the equation changes with different loading environments and then compares his model to experimental results. He states the data is in “very good agreement”; however, the data fit is not as close as he leads on. In a critical assessment of Kassapoglou’s model [20], the author states that his data fit is poor and his assumptions are premature and not as strong. Although his model seems to follow the general trend of the experimental data, the prediction must be much closer in order to pass the strict standards regulated by the FAA. Another statistical model exists by Diao, Ye, and Mai [21] that aims to develop a statistical cumulative damage model that predicts the residual strength and fatigue life of composite materials. The purpose of their methodology is to create a statistical model that incorporates all of the damage mechanisms, unlike past models in which the dominant failure mode is unclear [21]. The focus of this study, however, will not be statistics-based and will rely on experimental data and testing.

E. CURRENT MODEL USED TO PREDICT FATIGUE LIFE

A multiscale model described in Kwon and Darcy [22] will eventually be used to create a model that will predict the fatigue life of composites. This multiscale model links the micro-scale and macro-scale material properties using a unit cell approach and allows for micro-scale strains and stresses to be computed from macro-scale strains and stresses. They used the micro-scale strains and stresses were used for the different failure criteria described in their work and were able to predict the failure of the composite “very well.” For now, the correlation between the behavior of fatigue failure of the fiber and composite will be studied using a mathematical model. The mathematical model will attempt to relate the number of cycles until failure to the changing modulus of elasticity of the material.

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II. EXPERIMENTAL SETUP

In this study, two experimental tests were performed. The first test conducted was a low strain rate tensile test on an Instron machine. The specimen tested was epoxy resin with differing percent weights of carbon nanotube, glass fiber, and a composite of epoxy and glass fiber. Each specimen was tested in an Instron machine with a 2 mm/s extension rate and was tested until complete specimen failure. The second test conducted was a cyclic fatigue test on a Material Testing System (MTS) machine. The specimen tested on this machine were epoxy resin, glass fiber, and a composite of the epoxy and fiber. The importance of the tensile test is to determine the material properties of the resin and the fiber in order to conduct proper cyclic fatigue tests. The cyclic fatigue test results on the fiber and resin will be correlated to the performance of the composite.

A. INSTRON MACHINE TENSILE TESTING SETUP

1. Resin Testing Setup

As mentioned earlier, a low strain rate tensile test was conducted on several different types of resin. Four specimens of resin were tested; pure epoxy, epoxy with 0.05% weight carbon nanotube, epoxy with 0.1% weight carbon nanotube, and epoxy with 0.15% weight carbon nanotube. Five samples of each specimen were tested in the Instron machine. Each sample was molded into the typical “dog-bone” shape with near-constant dimensions; approximately 6 mm wide, 5 mm thick, with a gage length of about 11.1 mm. Each specimen was loaded in the Instron machine and tested until total failure. Figure 3 shows each specimen side by side before tensile testing.

Figure 3. From left to right, Pure Epoxy, Epoxy with 0.05% CNT, Epoxy with 0.1% CNT, and Epoxy with 0.15% CNT

2. Fiber Testing Setup

Glass fiber bundles were tested in the Instron machine at a low strain rate of 2mm/minute. Each bundle is 304.8 mm long, with an average width of 2.8 mm and an average thickness of 0.23 mm. Using the diameter of a single fiber filament measured by a scanning electron microscope (SEM) of 16.2 micrometers, and the manufacturer value of 2020 filaments in a bundle, the cross-sectional area of each bundle was calculated to be 4.42×10^{-6} m^2. In order to perform a tensile test on the fiber bundles, the ends needed to be attached to some sort of structure that would allow it to be clamped by the Instron machine on both ends. Two rectangular prisms, 40 mm in length, 6mm in width, and 25 mm in height, with a 6 mm by 3 mm oval hole in the middle of the top face was generated using generic PLA on an Ultimaker 3 3-D printer. All edges on this structure were filleted with a 1mm radius in order to try to decrease the stress concentration on the fiber bundle. Figure 4 shows the rectangular prism used for testing.

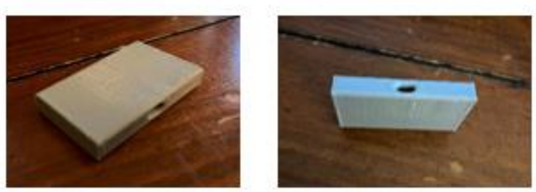

Figure 4. Rectangular Prism Made from Generic PLA

A fiber bundle was wrapped around the structure by putting it through the center hole, wrapping it around one side and weaving it back up through the hole and folding it over the other side. However, when testing this setup, several problems arose. When the structure with the bundle was clamped into the machine, the bundle often failed from the stress concentration caused by the clamp or from the stress concentration caused by being wrapped over the edge of the structure. An example of the stress concentration failure is shown in Figure 5

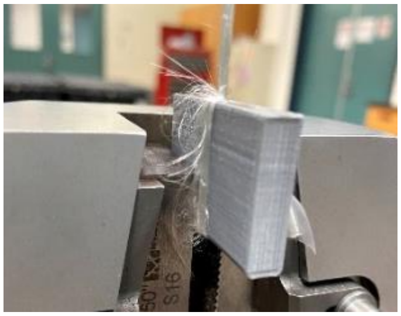

Figure 5. Failure of Fiber Bundle due to Stress Concentration from Top Left Corner of the Structure

In order to decrease the stress concentration from the edges caused by the tension, a new structure was made. This structure incorporates a cylindrical attachment on the rectangular prism that acts as a pulley system ensuring that the tension in the center of the fiber bundle is greater than the tension on the ends where the stress concentration would occur due to the clamping. This would ensure that the failure in the fiber bundle is due to the tensile testing and not any other outside factors. Figure 6 shows an example of this new structure. The rectangular portion is 6 mm thick and 70 mm long and 20 mm high. The attached cylinder is 20 mm in diameter, and the part on the end of the cylinder is 25 mm in diameter, used to keep the fiber bundle from slipping off. All edges are filleted.

Figure 6. Pulley-Like Structure for Testing

The fiber bundles were wrapped once around the cylinder and clamped at the ends on the cylinder so that the average gage length of the tests was about 78 mm. The gage length is measured from point the fiber is no longer in contact with the structure on both ends and once the fiber is pulled taught. This is illustrated by the black lines in Figure 7. The ends of the fiber bundles were wrapped in tape in order to decrease the stress concentration on the ends caused by the clamps. The setup of the tensile test with these new structures is shown in Figure 7.

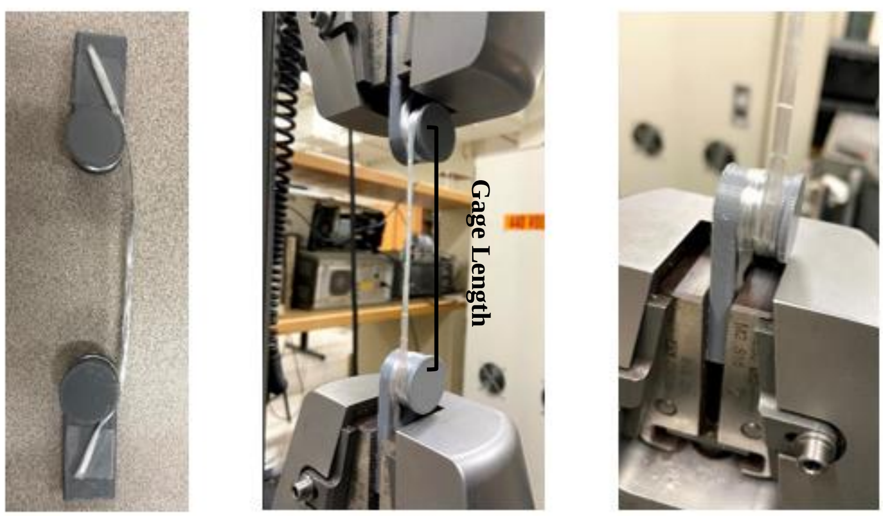

Figure 7. Setup for Fiber Bundle Tensile Testing

Testing the fiber bundles this way resulted in failure in the center of the bundles due to tensile failure rather than stress concentration failure at the ends. Figure 8 shows how the bundle failed. The splayed out fiber bundle indicates that there has been a failure and once the specimen is removed, the exact point of failure can be determined. For the specimen shown in Figure 8, the failure occurred in the middle of the bundle, indicated by the red box.

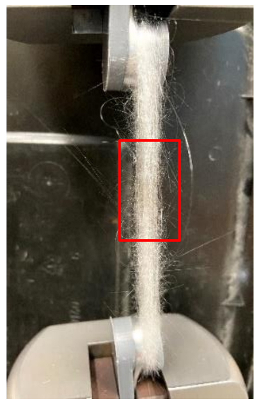

Figure 8. Failure of Fiber Bundle due to Tension

3. Composite Testing Setup

Most of the tensile tests of the composites made of epoxy resin and glass fiber were conducted at Korea Maritime and Ocean University for research collaboration. They tested three different composites with differing orientations of the fiber glass; 0°, 90°, and layered orientations of 0°/90°/90°/0°. The results of their tests were used to determine the material properties of the composite used in this study.

B. MTS TESTING SETUP

A MTS machine was used to conduct cyclic fatigue tests using the Basic Testware under the default test parameters. The tests for this machine were displacement controlled rather than force controlled for safety reasons so the fatigue tests were determined by the strain. The tests were run from 0 to Δ where Δ is the strain multiplied by the gage length. For each specimen, the target setpoint, which is the mean displacement that the test oscillates around, in the Basic Testware parameters was set to $\Delta/2$ and the amplitude was also set to a value of $\Delta/2$ to ensure that the test was run from 0 to Δ.

1. Fiber Testing Setup

The same PLA structure was used while testing the fiber bundles for cyclic fatigue. However, for this test, the bundle was wrapped around the circular end of the structure one and a half times so that the gage length of each specimen was roughly 57 mm. The hydraulic pressure for the upper and lower grips was set to 10 MPa so that the structures were not crushed but the pressure of the grips. The setup for the fiber bundle testing is seen in Figure 9.

Figure 9. Setup of Fiber Bundle Fatigue Test

Once the specimen was loaded in the machine, the upper grip was slowly moved upward until the force readings from the load cell were just above 0 N. This ensures that the fiber bundle is taught and there is no slack while the test is running. Tests were conducted at different strain magnitudes of 0.07, 0.05, and 0.02. Each test was run until complete failure, or until the force readings were consistently low (i.e., reading around 0 N), showing that there is no longer tension in the bundle when the maximum displacement is reached. Figure 10 shows a fiber bundle after failure due to cyclic fatiguing at a strain rate of 0.07.

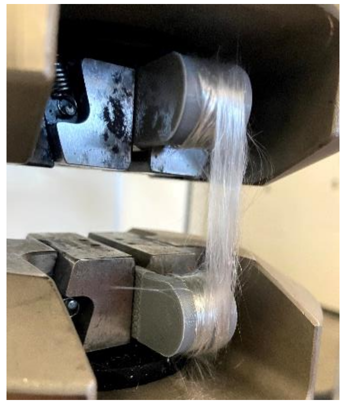

Figure 10. Failure of a Fiber Bundle at a Strain Rate of 0.07 after Approximately 160 cycles. Force Readings on the Load Cell Were below 1 N, Showing Failure of the Bundle

2. Resin Testing Setup

Due to restricted lab access, the resin samples themselves were not tested. Instead, a composite with fibers laid in a 90° orientation was tested. Fibers in a 90° orientation ensure that the resin will be the main load-bearing component so the properties of the resin under cyclic fatiguing can still be analyzed. These specimens were tested at low strain rates of 0.03, 0.02, and 0.01 strain because the resin is not reinforced by the fibers with this orientation and is not as strong as the fibers themselves.

3. Composite Testing Setup

The composites tested were made out of epoxy resin and glass fiber. Three different orientations were tested; 0°, 90°, and a layered orientations of 0°/90°/90°/0°. Each specimen tested had an average gage length of 38.1mm and an average cross-sectional area of 9.5mm. The composites were tested at 0.05 and 0.03 strain. Each test was run until the force readings were about 20% of the maximum initial force and leveled out. At this point, the main load-bearing capabilities of the structure has failed and should no longer be used. Figure 11 shows the setup of a 0° specimen and the failure of the specimen.

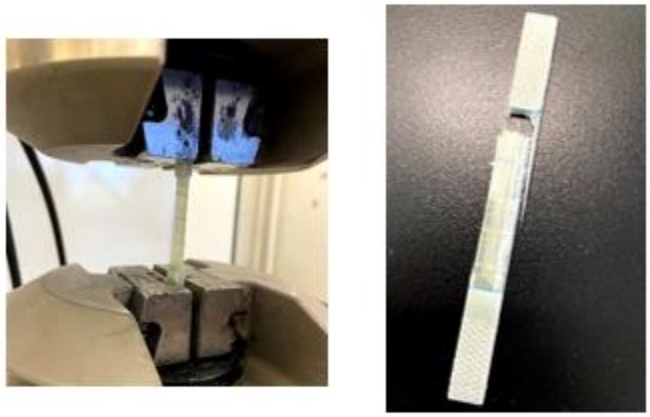

Figure 11. Setup of 0° Specimen (left) and Failure of 0° Specimen (right)

III. EXPERIMENTAL RESULTS

As stated earlier, two tests were conducted in this study; an Instron Machine tensile test and an MTS Machine cyclic fatigue test. The results from the tensile tests were used to determine the material properties of the resin, fiber, and composite. The ultimate tensile strength, failure strain, and the modulus of elasticity for each material were gathered from these tests. The modulus of elasticity is calculated using the following relationship between stress and strain

$$\sigma = E\varepsilon \,,$$

where σ is the stress in MPa, ε is the strain, and E is the modulus of elasticity in MPa.

The results from the cyclic fatigue tests were used to create a mathematical model for fatigue failure of fiber and composites. The number of cycles until failure, stress, strain, and modulus of elasticity were gathered from these tests.

A. TENSILE TEST RESULTS

The following results show the tensile test results of the epoxy resin, fiber-glass, and composites.

1. Tensile Test Results of Epoxy Resin

Several types of resin were tested during this study, however, since epoxy resin was used as the matrix for the construction of the composite, only the results of the tensile tests on the pure epoxy will be shown. Figure 12 shows the results of five different samples of pure epoxy resin tested at 2mm/min strain rate.

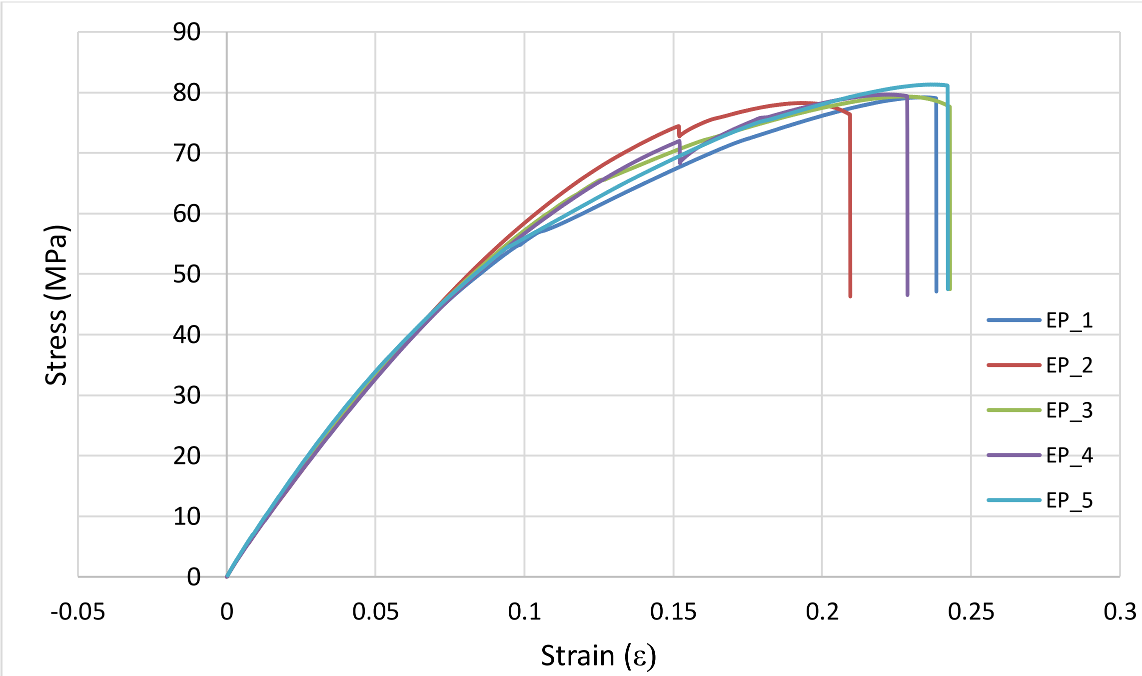

Figure 12. Tensile Test Results of Pure Epoxy

The figure shows consistent results for each test. Using this data, the material properties of the epoxy resin were determined. The modulus of elasticity was calculated to be about 600 MPa. The maximum tensile strength for this epoxy resin is seen to be about 80 MPa and the failure strain is 0.23.

2. Tensile Test Results of Glass Fiber

The tensile tests of the glass fiber were not as consistent as that of the epoxy tests. The results shown in Figure 13 show a wider dispersion of tensile data. However, this is not unexpected for fibers. Testing for the material properties of fiber is more complex; fibers are tested in bundles instead of individually so it is expected for the results from bundle to bundle to vary. The trends and order of magnitude between each sample are consistent.

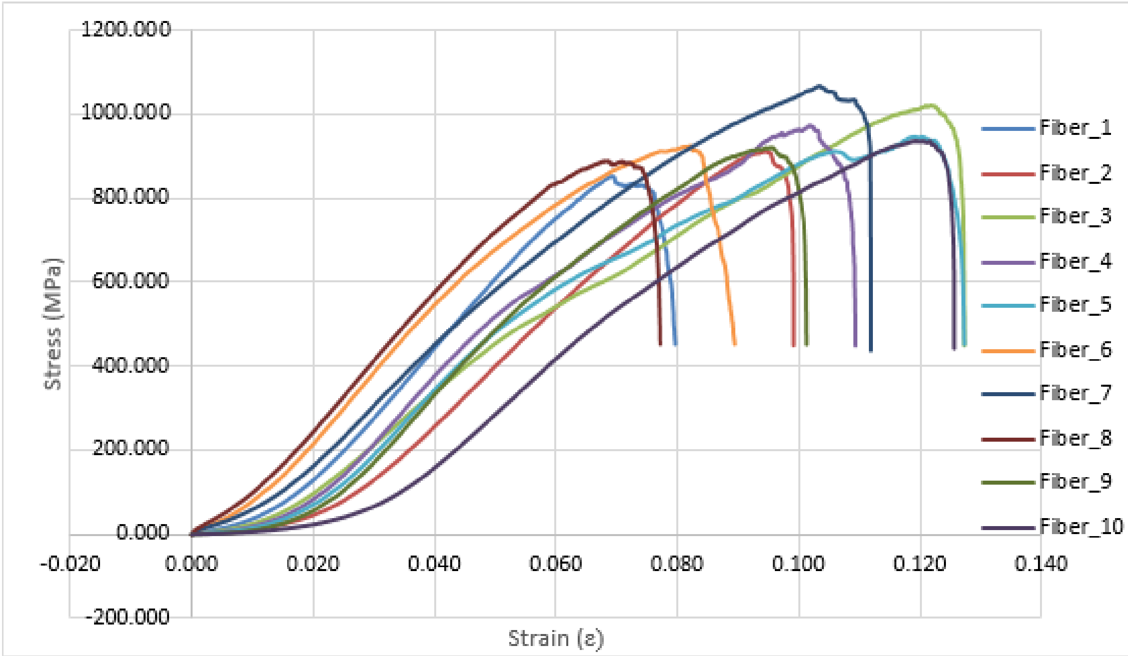

Figure 13. Glass Fiber Tensile Test Results

The maximum tensile stress, failure strain, and modulus of elasticity were calculated for each sample and then averaged and used as the material properties for the glass fiber used in this study. The modulus of elasticity was determined to be 9395.72 MPa (9.40 GPa), and the max tensile stress and failure strain were determined to be 961.4 MPa and 0.1027, respectively. Although the tests are similar between each sample, the results themselves are not as expected. The nominal published value for the modulus of elasticity of glass fiber is typically 70 GPa. This is about an 150% difference between this experimental data and the typical expected value. The difference may be due to the set-up of the tensile tests.

The gage length used for calculations for the tensile test was assumed to be the distance from the two points tangent to the PLA structure at both ends (shown in Figure 7). However, there could have been elongation along the circumference of the structure that was not taken in to account in the gage length. A shorter gage length means that the strain would larger and therefore lead to a smaller modulus of elasticity. In addition to this, there may also have been some slippage during the testing. The ends of the fibers were secured with tape and the clamps of the machines; however, this may not have held the ends as well as expected and caused the fiber bundle to slip showing a smaller modulus of elasticity than there should be.

3. Tensile Test Results of Composites

As mentioned earlier, the tensile tests of the composites were completed by Kyo-Moon Lee at Korea Maritime and Ocean University. Tests were conducted for composites with differing fiber orientations of 0°, 90°, and layered orientations of 0°/90°/90°/0°. The results are presented in tables showing the area, max load, max stress, and the failure strain. Five samples of each orientation were tested.

a. Zero Degree Composite Results

Table 1 shows the results of the tensile test data. The gage length of each sample was 40mm and the test was run at a strain rate of 1 mm/min.

Table 1. Tensile Test Results on Zero Degree Composite

Data	**Size**	**Area**	**Max Load**	**Max.Stren**	**Br Displace**	**Strain**	**Modulus of Elasticity**
Unit	**(WxT)mm**	**mm^2**	**N**	**MPa**	**mm**	**mm/mm**	**MPa**
SPEC	--	--	--	--	--	--	--
X1	10.230x1.360	13.913	14151.00	1017.106	4.83	0.12	8423.24
X2	10.020x1.370	13.727	13072.26	952.303	5.00	0.13	7618.42
X3	9.890x1.370	13.549	13229.17	976.395	5.13	0.13	7613.22
X4	10.480x1.350	14.148	14082.35	995.360	5.36	0.13	7428.06
X5	9.060x1.350	12.231	11365.91	929.270	4.35	0.11	8545.01

Table 1 shows the calculated failure strain and modulus of elasticity for each sample. The average values for the max tensile stress, failure strain, and modulus of elasticity of this composite is 973.8 MPa, 0.124, and 7925.4 MPa, respectively.

b. Ninety Degree Composite Results

Table 2 shows the results of the tensile test data for the 90° composite. This composite was much weaker than the other two, showing that the fiber is the main load-carrying component in the composite.

Table 2. Tensile Test Results on Ninety Degree Composite

Data	**Size**	**Area**	**Max Load**	**Max.Stren**	**Br Displace**	**Strain**	**Modulus of Elasticity**
Unit	(WxT)mm	mm^2	N	MPa	mm	mm/mm	MPa
SPEC	--	--	--	--	--	--	--
X1	9.640x1.460	14.074	343.23	24.388	0.76	0.02	1283.58
X2	10.110x1.540	15.569	323.62	20.786	0.85	0.02	978.16
X4	10.100x1.520	15.352	441.30	28.745	0.69	0.02	1666.38
X5	9.890x1.540	15.231	509.95	33.481	0.73	0.02	1834.58
X7	10.160x1.480	15.037	382.46	25.435	0.68	0.02	1496.18

Specimens 3 and 6 are not shown in the table because the results of the testing were incomplete. The average values for the max tensile stress, failure strain, and modulus of elasticity of this composite is 399.88 MPa, 0.02, and 1451.7 MPa, respectively.

c. Layered Composite Results

Table 3 shows the results of the 0°/90°/90°/0° layered composite. The results of this tensile test are as expected. The maximum tensile strength is lower than the 0° orientation and the breaking displacement is greater.

Table 3. Tensile Test Results on Layered Orientation Composite

Data	Size	Area	Max Load	Max.Stren	Br Displace	Strain	Modulus of Elasticity
Unit	(WxT)mm	mm^2	N	MPa	mm	mm/mm	MPa
SPEC	--	--	--	--	--	--	--
X1	10.610x1.470	15.597	6305.68	404.288	2.99	0.07	7202.07
X2	10.160x1.480	15.037	6462.58	429.779	2.94	0.07	8398.65
X3	9.750x1.440	14.040	6080.12	433.057	2.99	0.07	8883.23
X4	10.430x1.490	15.541	6894.08	443.606	3.14	0.08	7681.96
X5	9.950x1.470	14.627	6384.13	436.462	3.00	0.08	8300.79
X6	10.090x1.490	15.034	6325.29	420.732	2.97	0.07	8349.42

The average values for the max tensile stress, failure strain, and modulus of elasticity of this composite is 427.98 MPa, 0.08, and 8136.02 MPa, respectively.

The average values from the tensile tests were used to determine the set-up of the cyclic fatigue tests. As mentioned earlier the fatigue tests were displacement controlled rather than force controlled so the failure strain from the tensile test determined the strain at which the fatigue would be done.

B. CYCLIC FATIGUE RESULTS

The cyclic fatigue tests were run from 0 to Δ where Δ is the displacement for different strains. Based on the results from above, each material was tested at different strains until failure. The fiber bundles, which showed high failure strain, were tested with higher displacements while the ninety-degree composites, which showed low failure strains were tested at low displacements. Table 4 shows a summary of the test matrix and which materials were tested at what strains.

Table 4. Cyclic Fatigue Testing Matrix

Strain	**0.07**	**0.05**	**0.03**	**0.02**	**0.01**
Material	mm/mm	mm/mm	mm/mm	mm/mm	mm/mm
Glass Fiber	X	X	X	X	
0° Composite		X	X		
0°/90°/90°/0° Composite		X	X		
90° Composite				X	X

All of these tests were conducted, however, not all of the tests were successful and gave reliable data. The glass fiber tested at 0.03 strain showed very unexpected results that were most likely due to problems with the pulley structures that were used. The test at 0.02 lasted over a million cycles and terminated due to time constraints. The layered composite tested at 0.05 strain failed almost immediately upon starting the test and could not be analyzed for cyclic results. The same thing happened for the 90° composite at 0.02 and 0.01 strain; the specimen failed almost immediately upon the start of the test and the results were only used to verify that the fiber is the main load-carrying component of the composite and that the failure of the composite is more related to the failure of the fiber than that of the matrix. Table 5 shows which tests had reliable data and were used for analysis.

Table 5. Cyclic Fatigue Tests Used for Analysis

Strain	**0.07**	**0.05**	**0.03**	**0.02**	**0.01**
Material	mm/mm	mm/mm	mm/mm	mm/mm	mm/mm
Glass Fiber	X	X			
0° Composite		X	X		
0°/90°/90°/0° Composite			X		

The displacement controlled fatigue tests recorded displacement, force, and the number of cycles for each test. Although the force fluctuated with each cycle, the results will only present the maximum force at each cycle versus the number of cycles so that the trend of decreasing strength at each cycle until failure can more easily be seen. Figure 14 shows the cyclic trend of a test just to show that the tests are a tension-tension test with the force going from 0-F where F is the peak force occurring at Δ.

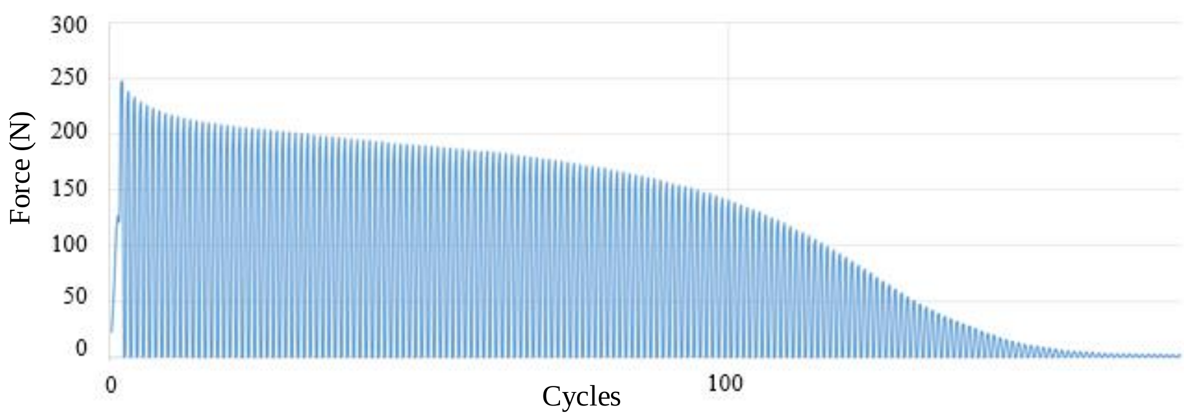

Figure 14. Illustration of the Cyclic Fatiguing of a Fiber Bundle at 0.07 Strain

Each test was run until failure; for the fatigue tests, failure will initially be defined as the peak strength at N cycles being lower than 20% of the initial peak strength. This ensures that the "failure" point no longer has the ability to withstand substantial loads while also not having to wait for the force readings to show absolute 0 N.

1. Cyclic Fatigue Results of Glass Fiber

The glass fiber bundles were tested at 0.07 strain and 0.05 strain. Two specimens were tested at 0.07 and three were tested at 0.05. Figures 15 and 16 show the results of the 0.07 strain test and the 0.05 strain test, respectively.

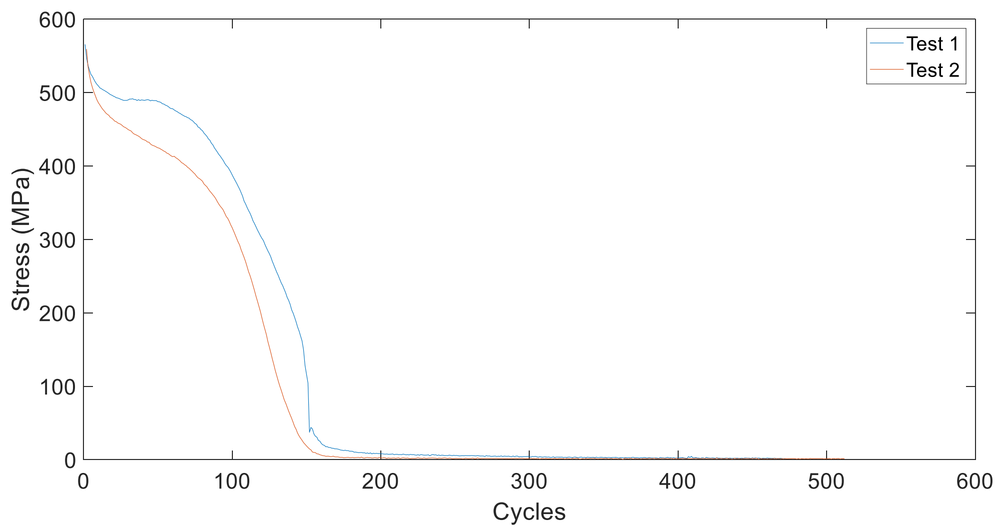

Figure 15. Fatigue Results for Glass Fiber at 0.07 Strain

The line in this figure represents the peak stress at each cycle showing the decrease of strength over time. It can be seen that both of the bundles fail after about 160 cycles where the stress is close to zero. The figure shows similar results between the two tests with a similar trend. However, Figure 16 also shows similar results and trends between each test but the trend is much different than that seen in Figure 15. For the 0.07 strain, the peak stresses seem to decrease at a higher rate than the peak stresses for the 0.05 strain.

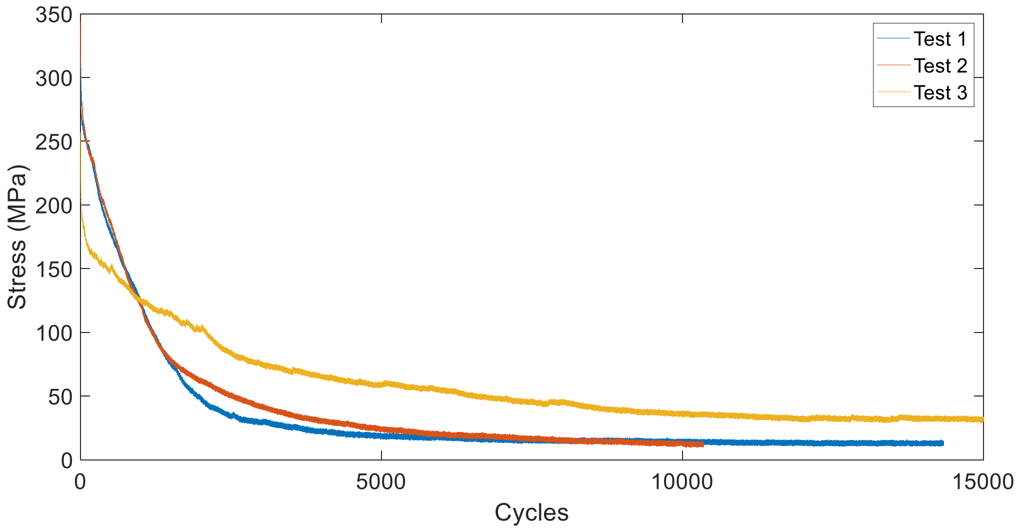

Figure 16. Fatigue Results for Glass Fiber at 0.05 Strain

The figure shows that the fiber fails at around 3000 cycles for each test. The maximum stress is approximately 300 MPa meaning the defined "failure" stress is 30 MPa which occurs around 3000 cycles. The results between the first two specimens are almost the same, while the third specimen shows slightly off. This could be due to improper set up of the fiber bundle, maybe it was not completely taught before starting the test and may have some slack in it. Because of the close similarities between specimens 1 and 2, these will be the accepted values for the fiber bundle at 0.05 strain for this study.

2. Cyclic Fatigue Results of Composites

About three to four samples of each composite were tested at the strains described in Table 5. The failure of the composite was defined the same way as the fiber where once the peak force was below 20% of the initial force, the test was stopped. This was more important in the composite testing because even when most of the composite failed, there was still some residual strength from the fiber alone which explains the force readings at the end of the tests. Although residual strength from the fibers exist, the composite itself no longer has the same load-carrying capability and is to be assumed to have "failed."

a. Zero Degree Composite Results

The zero degree composites were tested at 0.05 strain and 0.03 strain; the results are shown in Figures 17 and 18, respectively. Again, the lines represent the peak stress at each cycle.

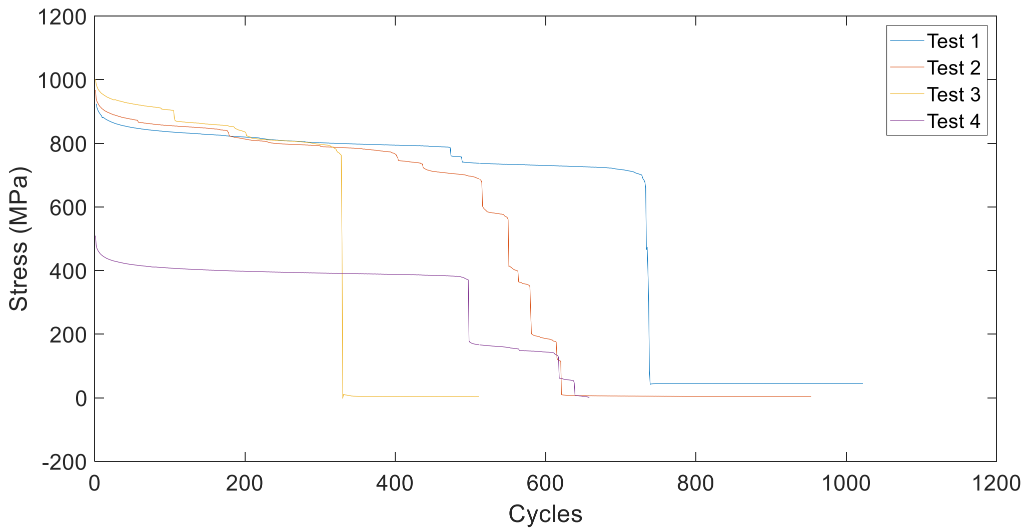

Figure 17. Cyclic Fatigue of 0° Composite at 0.05 Strain

Specimens 1, 2, and 3 show similar results starting at the same initial peak strength with similar cycles until failure. The point of certain failure for these composites can be seen in the large drop off and immediate decrease of strength to almost 0 MPa. The 0° composite fails at approximately 600 cycles.

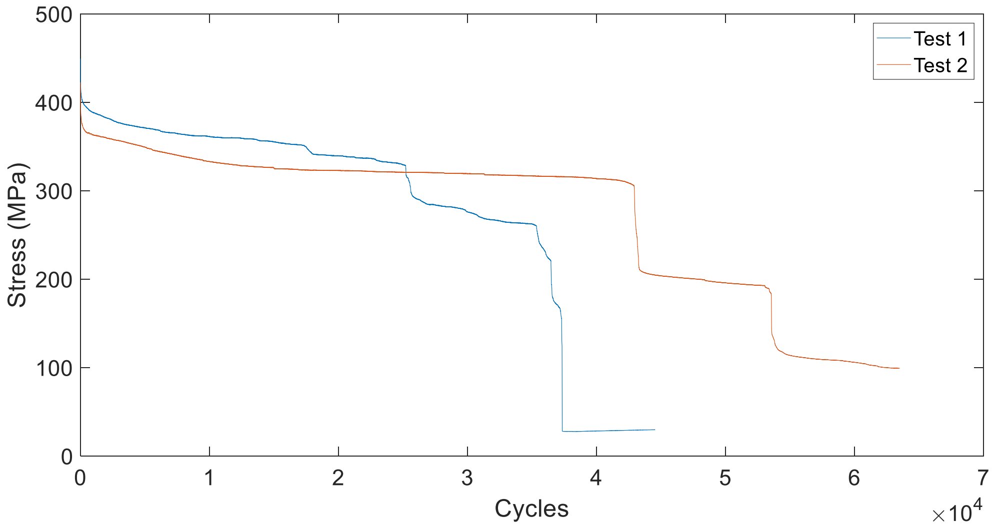

Figure 18. Cyclic Fatigue of 0° Composite at 0.03 Strain

Both specimens 1 and 2 show consistent results in this test. The initial peak strength is much lower than that of the tests at 0.05 strain, and the cycles until failure are about 100 times greater, which is expected. For 0.03 strain, the number of cycles until failure is approximately 40,000 cycles.

b. Layered Composite Results

The results of the layered composites were less consistent than that of the zero degree composite tests. Figure 19 shows the results of the layered composite at 0.03 strain. The results of these tests are not surprising though because of the complex nature of composites in general. Even though the results were not consistent, the cycles until failure were on the same order of magnitude and the initial peak stress was also close in value.

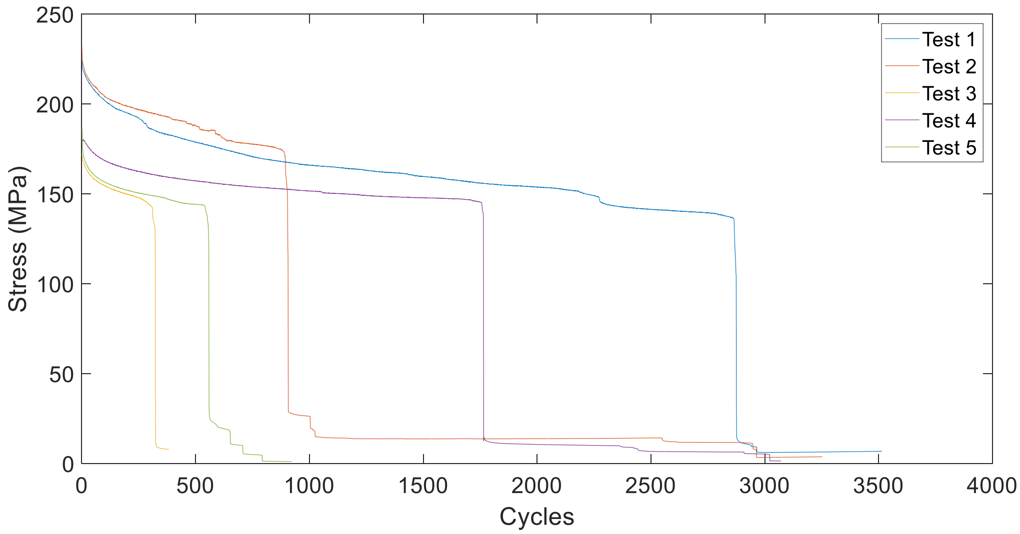

Figure 19. Cyclic Fatigue of 0°/90°/90°/0° Composite

Averaging out the values, the number of cycles until failure for the layered composite is about 1,300 cycles. Both tests at 0.05 strain and 0.03 strain for both types of composites follow the same trends where the strength decreases to a point and then drops off suddenly to failure. Table 6 is a tabular summary of the results, showing the peak stress and cycles of failure for each test.

Table 6. Tabular Summary of Results

Strain	**0.07**		**0.05**		**0.03**	
	Max Stress	Cycles to Failure	Max Stress	Cycles to Failure	Max Stress	Cycles to Failure
Glass Fiber	580 MPa	160	300 MPa	3,000	--	--
0° Composite	--	--	1,000 MPa	600	400 MPa	40,000
0°/90°/90°/0° Composite	--	--	--	--	200 MPa	1,300

Upon further review of the composite failure, it can be seen that once the peak stress reached about 70% of the initial stress, which is when the sudden drop occurred. For the 0° composite at 0.05 strain, the initial stress was 1000 MPa. At 600 cycles just before the sudden drop, the stress is about 700 MPa which is 70% of the initial stress of 1000 MPa. This is seen again for 0.03 strain; the initial stress is about 400 MPa and the stress before failure is about 290 MPa, just below 300 MPa: just between 70–75% of the initial stress. The same trend is observed for the layered composite: the initial stress is about 200 MPa and the failure stress is approximately 145 MPa which is 72% of the initial stress. Because of this, the failure will now be defined as reaching 70% of the initial stress rather than 20%. This will allow for a more uniform analysis between the fiber tests and the composite tests.

IV. MATHEMATICAL MODEL FORMULATION AND ANALYSIS

The experimental data shows that stress decreases with increasing cycles. Since the strain remains constant, this also shows that the elastic modulus decreases with increasing cycles. A mathematical model will be formulated to predict the elastic modulus as a function of the number of cycles for both the fiber and the composites. As stated earlier, the data will now be analyzed from the start to 70% of the initial maximum and failure cycles will be the number of cycles until the 70% point is reached. The stress versus cycles graphs will be transformed to elastic modulus versus cycles graphs. Figures 20, 21, and 22 show the transformed graphs for the fibers and the composites, respectively.

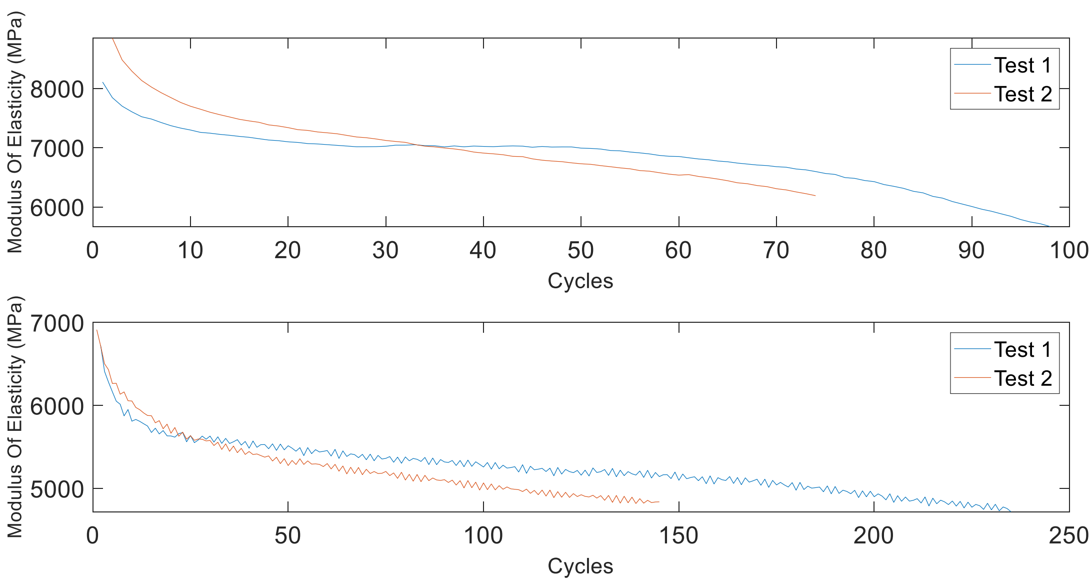

Figure 20. Modulus of Elasticity versus Number of Cycles for Fiber at 0.07 Strain (top) and 0.05 Strain (bottom) to 70% of Initial Modulus

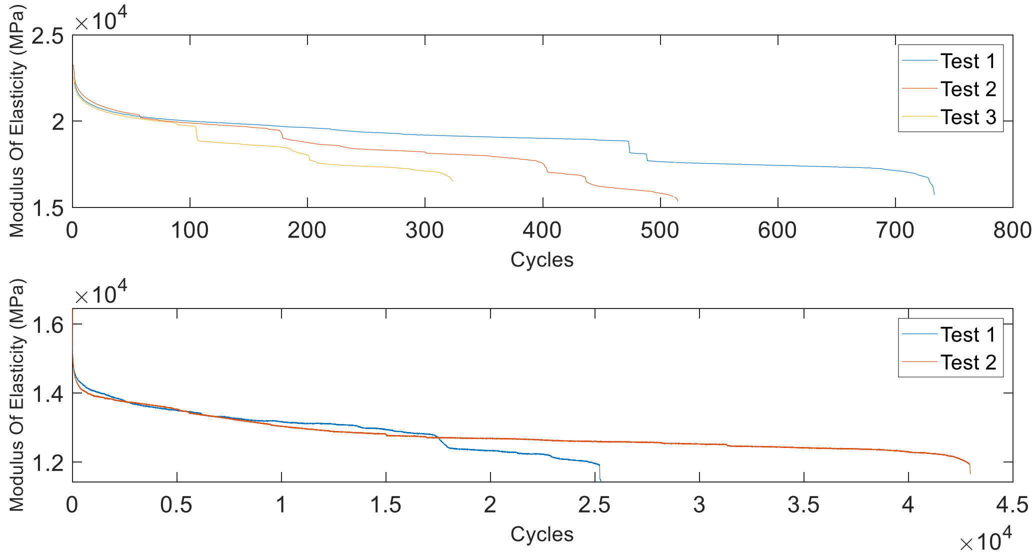

Figure 21. Modulus of Elasticity versus Cycles for Zero Degree Composite at 0.05 Strain (top) and 0.03 Strain (bottom) to 70% of Initial Modulus

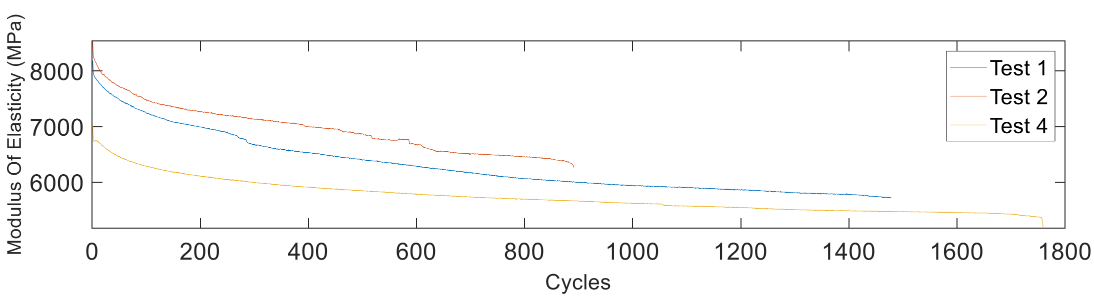

Figure 22. Modulus of Elasticity versus Cycles for Layered Composite at 0.03 Strain to 70% of Initial Modulus

For these graphs, it is important to note that the outliers were not considered during analysis; for the fiber test at 0.05 strain, Test 3 was not included, for the 0° composite test at 0.05 strain, Test 4 was not included, and for the layered composite test at 0.03 strain, Test 3 and Test 5 were not included. This allows for a more consistent analysis and better fit for mathematical model predictions. It is also important to note that although the strain was constant, the Elastic Modulus was calculated by using the recorded strain at that point rather than using the constant strain for each test. Table 7 shows the updated summary of the results assuming a failure occurs at 70% of the initial modulus. Since the failure between each specimen varied for each test, the number of cycles to failure were averaged between them. For example, for the fiber at 0.07 strain, Test 1 shows 98 cycles to failure and Test 2 shows 73 cycles to failure so the average would be 86 cycles.

Table 7. Tabular Summary of Results of 70% Failure

Strain	**0.07**		**0.05**		**0.03**	
	Failure Modulus	Cycles to Failure	Failure Modulus	Cycles to Failure	Failure Modulus	Cycles to Failure
Glass Fiber	5,980 MPa	86	5,000 MPa	196	--	--
0° Composite	--	--	16,290 MPa	513	12,250 MPa	30,000
0°/90°/90°/0° Composite	--	--	--	--	5,940 MPa	1,350

A. MATHEMATICAL MODEL FORMULATION

A mathematical expression was formulated to predict the fatigue failure shown in the experimental results. The results showed that the elastic modulus was reduced with the increasing number of cycles and that this decrease could be represented by an exponential decay pattern. As described earlier, it was also assumed that the samples failed when elastic modulus was reduced to about 70% of the initial modulus. Based on these experimental observations, the requirements of the mathematical model are as follows: 1) it must be a function of the applied strain and the number of cycles 2) when the applied strain is equal to or greater than the failure strain, the expression should predict immediate failure for the first cycle 3) when the number of cycles reaches the failure cycle, the modulus should be 70% of the initial modulus. Based on these requirements and the observation that the results showed an exponential decay and the curve became flat as it reached the failure cycle, the general expression was proposed

$$E(N) = \frac{e^{\left[-\alpha\left(\frac{\varepsilon_a}{\varepsilon_f}\right)^2 * N\right]} + C\left(\frac{N_f - N + 1}{N_f}\right)^{\beta}}{1 + C} * E_{max},$$

where E(N) is the reduced modulus after *N* cycles, ε_a is the constant applied strain for each case, ε_f is the failure strain of the material, N_f is the number of failure cycles taken from the values in Table 7, E_{max} is the initial modulus for each case, and α, β, and C are all constants. For this expression, C is a constant in the form

$$C = c + \left(\frac{\varepsilon_a}{\varepsilon_f}\right) * 6.5 .$$

B. MATHEMATICAL MODEL VALIDATION

The mathematical expression was tested for fiber fatigue failure and composite fatigue failure for comparison. The values for α, β, and *c* vary for each test to have a perfect fit; however, in order to create a model that can predict fatigue failures of different kinds of samples consistently, the fiber tests will be evaluated using the same constants and the composites will be evaluated using the same constants.

1. Fiber Experimental and Predicted Results

The values for α, β, and *c* for the fiber tests are 0.4, 0.055, and 2.7, respectively. Even though each test in the different strain cases followed the same trend, their values still differ. Because of this, when fitting the mathematical expression, it was fit more closely to one of the curves rather than trying to fit both of them. Figures 23 and 24 show the experimental results in comparison to the mathematical prediction with these constants for both the 0.07 strain and 0.05 strain. The black circle on each figure represents the point at which the reduced modulus is 70% of the initial modulus showing the failure point predicted by the model.

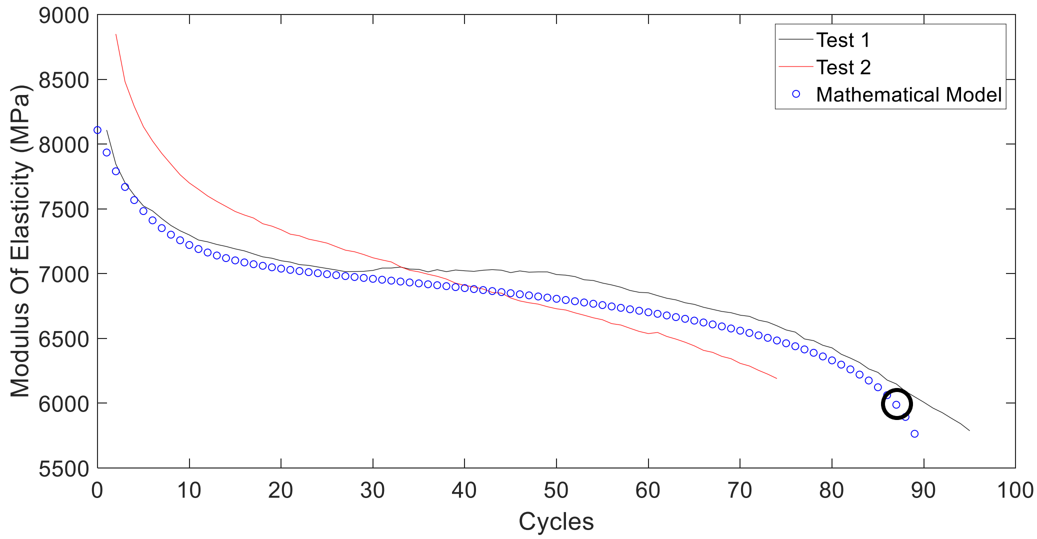

Figure 23. Mathematical Prediction of Reduced Modulus of Elasticity with Number of Cycles Compared to Experimental Results of Fiber at 0.07 Strain

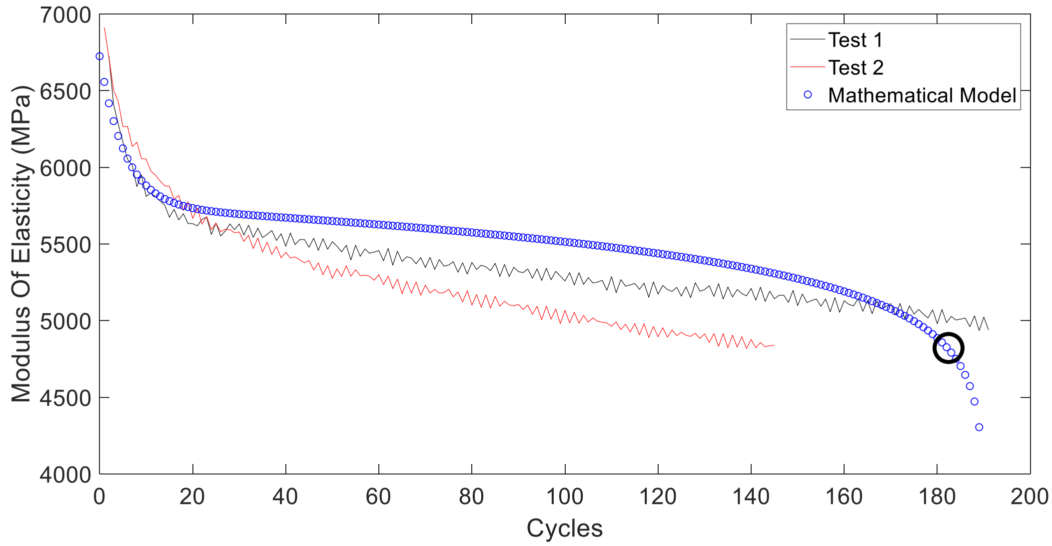

Figure 24. Mathematical Prediction of Reduced Modulus of Elasticity with Number of Cycles Compared to Experimental Results of Fiber at 0.05 Strain

The mathematical model closely predicts the behavior of Test 1 for both cases. With these specific constants, the mathematical expression underestimates the reduced modulus for the strain at 0.07 and overestimates the modulus for strain at 0.05 which makes it more difficult to find the same constants to fit both more closely. Although the model is slightly off when predicting the reduced modulus for each case, it does well in predicting the failure cycles for the modulus 70% of the initial modulus.

In the case of 0.07 strain, the initial modulus was set to about 8,100 MPa meaning the failure modulus would be at 5,670 MPa. The prediction shows that at around 5,700 MPa and 89 cycles, the modulus starts to decrease at a quicker rate indicating a sudden drop in the modulus, or failure. The actual experimental results from Table 7 show that the fiber fails after 86 cycles. In the case of 0.05 strain, the initial modulus was set to about 6,725 MPa and the failure modulus would be 4,700 MPa. The model indicates that at around 4,750 MPa and 184 cycles, the modulus starts to decrease at a quicker rate just before the sudden drop off. The actual experimental results from Table 7 show that the fiber fails after 196 cycles. The model was able to predict the failure cycle within 6% of the experimental results for both cases; 3% for the fiber at 0.07 strain and 6% for the fiber at 0.05 strain. This shows that the model is reliable in determining the number of cycles until failure for glass fiber.

2. Composite Experimental and Predicted Results

The values for α, β, and c for the composite tests are 0.1, 0.07, and 3, respectively. Although these constants are not the same value as those used in the fiber model, they are relatively close. The end goal of this research is to create a model that can predict the behavior for all cases using the same equation and the same constants; however, the focus of this study is determining a relationship and correlation between the two behaviors which is what this expression shows. Similarly to the fiber results, the expression with these constants over predicts and under predicts the reduced modulus for the different tests.

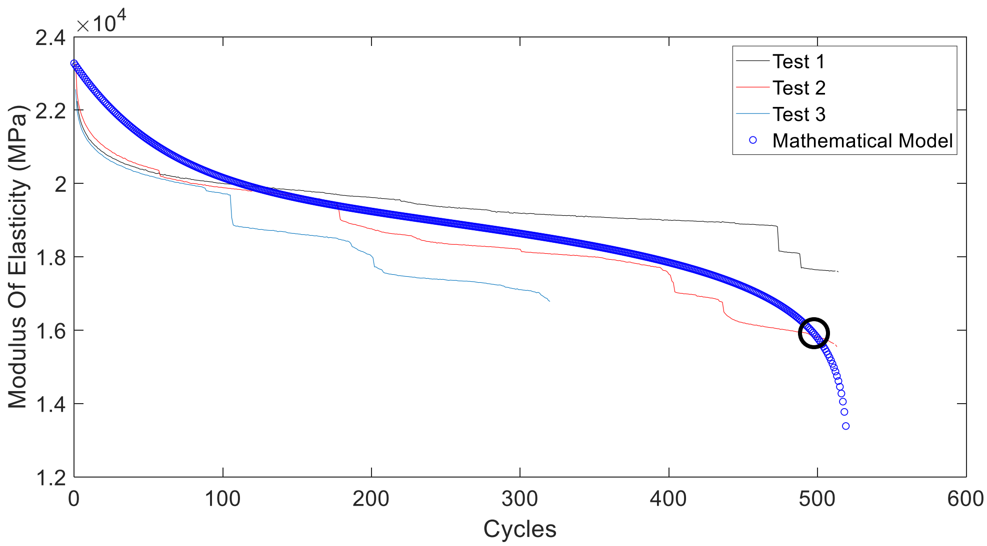

Figure 25. Mathematical Prediction of Reduced Modulus of Elasticity with Number of Cycles Compared to Experimental Results for 0° Composite at 0.05 Strain

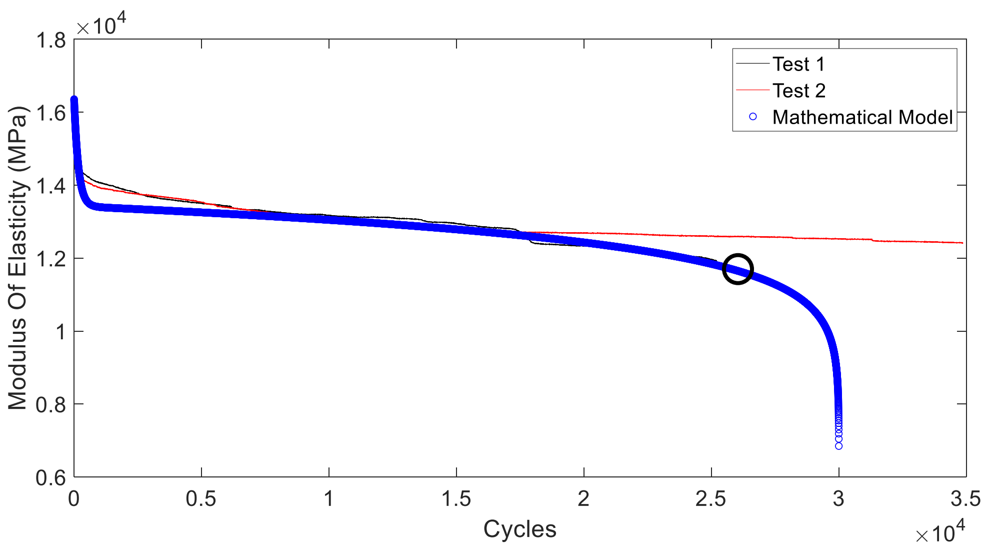

Figure 26. Mathematical Prediction of Reduced Modulus of Elasticity with Number of Cycles Compared to Experimental Results for 0° Composite at 0.03 Strain

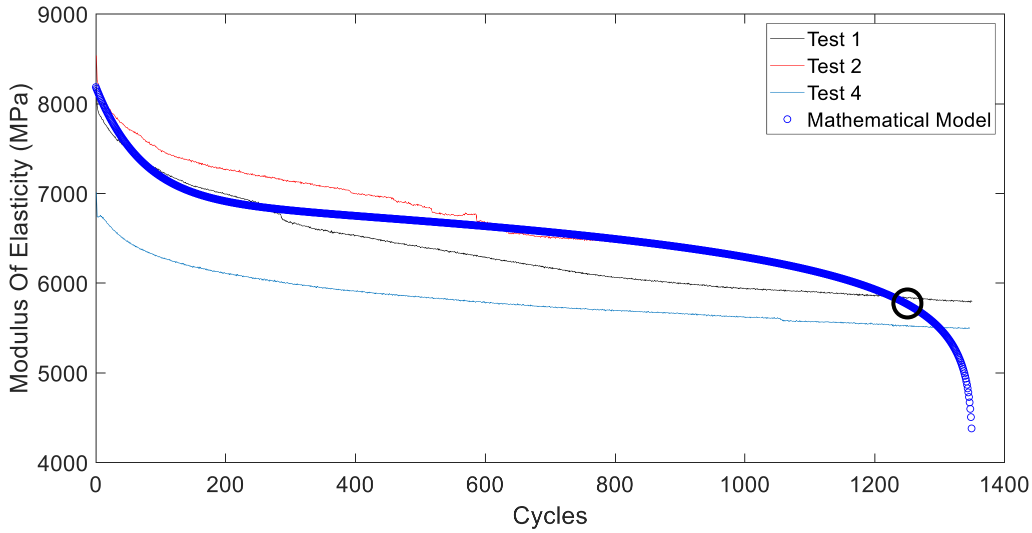

Figure 27. Mathematical Prediction of Reduced Modulus of Elasticity with Number of Cycles Compared to Experimental Results for Layered Composite at 0.03 Strain

For the zero degree composite, it can be seen that the model does a poor job at predicting the reduced modulus for the initial 20% of the cycles; the model greatly overestimates the values for 0.05 strain while it underestimates the values for 0.03 strain. However, the model seems to follow the same trend and becomes more accurate in predicting the reduced modulus as the cycles increase. For the layered composite, the model does a good job predicting the initial decrease of elastic modulus but then overestimates the values in the middle. Even though the reduced modulus are not predicted as well, the model does a better job predicting the actual failure cycle.

For the zero degree composite at 0.05 strain, the maximum modulus of elasticity is 23,270 MPa so the failure modulus would be about 16,300 MPa. The model shows that the failure modulus 16,292 MPa occurs at 488 cycles. The experimental results from Table 7 state that the failure cycle is 513 cycles which has a 5% difference from the failure cycles predicted. At 0.03 strain, the initial modulus is 16,360 MPa which makes the failure modulus 11,450 MPa. The model predicts that the failure modulus 11,450 MPa occurs at 26,907 cycles and then the rate of reduced modulus quickly increases as the model goes towards 30,000 cycles. This prediction is within 10% of the experimental results. Lastly, for the layered composite at 0.03 strain, the initial modulus was 8,170 MPa and the failure modulus is 5,720 MPa. The model shows that the failure modulus 5,724 MPa occurs at 1,260 cycles which is a 7% difference from the experimental value of 1,350 cycles in Table 7. The mathematical expression used with the specified constants for composite materials shows that it is less accurate in predicting the reduced modulus at each cycle, but is able to predict the failure cycle of each composite within 12% of the experimental data. An important thing to note is that the experimental data itself had great range in reduced elastic moduli and number of failure cycles and the model was able to predict values within the range of the experimental values and within 12% of the average of the experimental values. This shows that the model can predict the number of cycles until failure for composites with differing orientations; however, it is not as accurate in predicting the reduced modulus at each cycle before failure.

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V. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

The long-term goal of this research is to create a multi-scale model based on the unit-cell approach, described in [22], that will predict the fatigue failure of composites with relation to the fiber and matrix it is composed of. The focus of this study is to determine a correlation between the failure of fibers and matrix with the failure of composites. In this experiment, glass fiber and epoxy resin will be used to create composites with differing fiber orientations. The different composites consisted of 0°, 90°, and layered 0°/90°/90°/0° fiber orientations. The glass fiber, epoxy resin, and composites were each tested in an Instron machine tensile test and in an MTS machine cyclic fatiguing test.

The results of the tensile tests gave the material properties of each specimen that was used for determining the cyclic fatigue test setup. While conducting the tensile tests it was noted that the experimental modulus of elasticity (9.4 GPa) for the glass fiber was much lower than the nominal published value (70 GPa). This could be due to the fiber test setup; there could possibly be slippage of the fiber on the PLA cylindrical structure. Also, there may be extra stretching around the structure that was not taken into account for the gage length. The cyclic fatigue tests were displacement controlled and applied a constant strain to each specimen. Tests were conducted at differing strain magnitudes of 0.03–0.07. The 90° composite was much weaker than the other composites and failed immediately even at 0.01 strain. The 0° composite was conducted at 0.05 and 0.03 strain while the layered one was only conducted at 0.05 strain. The fiber also only had two tests; 0.07 and 0.05 strain. While attempting to conduct the test at 0.03 strain, the machine/pieces malfunctioned and the data was no good and could not be used.

The cyclic fatigue results for the composites show similar trends in that the stress decreases to a point and then drops off suddenly to failure. Upon further review, it can be seen that the stress decreases to approximately 70% of its initial stress before failure. This observation defined the failure point in this study to be 70% of the initial value. Defining this as the failure point created a more uniform analysis between the fiber results and the composite results for each test. Another important observation is that since the stress is decreasing with time and the applied strain remains constant, then the elastic modulus is decreasing with the increasing number of cycles. The results of the cyclic fatigue tests for each specimen were analyzed using an elastic modulus versus number of cycles plot in which the failure cycle is the point at which the reduced modulus is 70% of the initial modulus. While reviewing the plots, it was noted that the elastic modulus of the 0° composite varied greatly between the two tests, 25 GPa and 16 GPa, and these values are much higher than the elastic modulus calculated from tensile tests, about 8 GPa. This could possibly be due to the data received from the Korea Maritime and Ocean University; the data only specified the maximum load, stress, and breaking displacement. The recorded data from the tensile test was not received so it was difficult to tell if the breaking displacement occurred in the elastic region of the stress-strain curve. Instead, it was assumed that E was just the maximum stress divided by the failure strain which could cause it to be less than it should be and could help explain the discrepancy between the cyclic fatigue values and the tensile test values. Also, due to time constraints, the tensile tests of the composites were never tested in this study so the data was not validated.

A mathematical expression was created to relate the reduction of the modulus of elasticity to the applied strain and the number of cycles. It is important to state that even though the elastic modulus of the fibers and composites did not match the nominal accepted values, this did not affect the equation because they were normalized with respect to the initial modulus value. This mathematical model had to satisfy several requirements based on the data observations such as the 70% failure assumption and the exponential decay behavior. The mathematical model was able to predict the number of failure cycles within 12% of the experimental results for each case. Even though the model did not successfully predict the reduced modulus at each cycle for each test, the goal of the study is to be able to predict the failure cycle which was still achieved within 12% accuracy. Predicting the reduced modulus is a means for the overall purpose of predicting the failure cycle. Therefore, the exact prediction of the change in the modulus is less critical than the prediction of the failure cycles.

In general, the experimental results gave a wide range of data which made it more difficult in determining the accuracy of the model. The experimental data was averaged and compared to the model, however more consistent results are needed in order to more easily validate the success of the mathematical model.

B. FUTURE WORK

This study focused on finding a relationship between the failure behavior of fibers and the failure behavior of composites. The results of the mathematical expression were somewhat successful in relating the two, however going forward, the expression should be adjusted so that it can predict the failure for both the fiber and the composite using the same equation and constants. In addition to this, the model should be able to better predict the reduced modulus after each cycle. Due to setbacks from COVID-19, major time constraints were placed on this study, as a result, the experimental data was not very consistent and there was little time to repeat tests to get better data. One of the major problems in this study was the inconsistency of the elastic modulus with accepted values and experimental values. There was clearly a problem in the test setup that led to this inconsistency and more tests need to be conducted for both the fiber and the composite to get more reliable results. The next step after fine-tuning the mathematical model would be to create the multi-scale model that will be able to accurately predict fatigue failure and service life.

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